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Capture of solar wind alpha-particles by the Martian atmosphere

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[1] Integration along He^{++} test-particle trajectories in the self-consistent electromagnetic fields generated by three-dimensional hybrid simulations of the solar wind/Mars interaction is used to evaluate the removal of solar wind α -particles due to charge-exchange processes with neutral species of the Martian exosphere. The total removal rate of solar wind He^{++} ions, transformed into either singly ionised or neutral helium, is equal to $6.7 \times 10^{23} \text{ s}^{-1}$, which corresponds approximately to 30% of the flux of solar α -particles through the planetary cross-section. The deposition rate of helium neutral atoms, created by double electronic capture on exospheric oxygen, impacting the exobase, and penetrating below where it can be trapped, is about $1.5 \times 10^{23} \text{ s}^{-1}$. That means an important contribution of the solar wind source to the helium balance of the Martian atmosphere. The implantation of the solar helium into the Martian atmosphere shows an asymmetry related to the orientation of the motional electric field of the solar wind, $-V_{SW} \times B_{IMF}$. **Citation:** Chanteur, G. M., E. Dubinin, R. Modolo, and M. Fraenz (2009), Capture of solar wind alpha-particles by the Martian atmosphere, *Geophys. Res. Lett.*, 36, L23105, doi:10.1029/2009GL040235.

1. Introduction

[2] Helium in the atmospheres of the terrestrial planets is generally produced by the surface outgassing of the helium atoms produced by the radioactive decay of uranium (U) and thorium (Th) in the planetary interiors. The first remote measurements of He at Mars were made on the EUVE satellite orbiting the Earth [Krasnopolsky *et al.*, 1994]. Using He -584Å airglow observations Krasnopolsky and Gladstone [1996] concluded that the helium mixing ratio is equal to 4 ± 2 ppm in the lower atmosphere and the escape rate is $(7.2 \pm 3.6) \times 10^{23} \text{ s}^{-1}$. The first in-situ measurements of ionized planetary helium picked up by the solar wind were carried out onboard the Phobos-2 spacecraft [Barabash and Norberg, 1994; Barabash *et al.*, 1995]. The reported escape fluxes of He^+ ions equal to $(1.2 \pm 0.6) \times 10^{24} \text{ s}^{-1}$ are consistent with the estimations made by Krasnopolsky and Gladstone [1996] taking into account the difference in solar activity. Such high values of the non thermal losses imply that helium formed by the radioactive decay of U and Th could be fully lost in less than one

million years: a lifetime of helium on Mars is 0.13 million years [Krasnopolsky and Gladstone, 2005], much shorter than the age of the latest volcanism which is estimated at a few million years [Neukum *et al.*, 2004]. Therefore outgassing of radiogenic helium may be a minor source of helium on Mars. Krasnopolsky and Gladstone [1996] have suggested that $\sim 70\%$ of the required source flux is supplied by the capture of solar wind α -particles with efficiency $\sim 0.3 \pm 0.1$. Recent longer-exposure EUVE observations of the He -584Å emissions have led to an improved value of the mixing ratio equal to $(10 \pm 6 \text{ ppm})$ although the estimate of the total loss of helium ($8 \times 10^{23} \text{ s}^{-1}$) is almost unchanged [Krasnopolsky and Gladstone, 2005]. Krasnopolsky and Gladstone [2005] have concluded that the capture of solar wind He^{++} ions can be the only substantial source of helium on Mars. However, the efficiency of this process has not yet been tested experimentally or accurately tested by global simulations of the solar wind/Mars interaction. The deposition of solar wind matter on Mars was first evaluated by Brecht [1997] by means of mono-species three-dimensional hybrid simulations. In these early simulations, the IMF and solar wind protons interacted with a bare and conducting sphere without atmosphere. The deposition of solar wind protons on the surface was of 3–30% depending upon the ram pressure. A simple scaling to alpha-particles yields the deposition rate of $1.3 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$. However, the nature of the Martian obstacle to the solar wind is more complicated. The solar wind interacts directly with the planetary upper atmosphere and ionosphere inducing a magnetosphere by piling-up and draping the interplanetary magnetic field around the obstacle. This induced magnetosphere protects the low altitude ionosphere and atmosphere from a direct exposure to the solar wind. It is also worth noting that due to their different gyroradii α -particles and protons have different dynamics in the Martian environment, resulting in different deposition rates which might not be related by a simple scaling.

[3] Recently, Modolo *et al.* [2005] designed a more sophisticated 3-D hybrid model including the dynamics of both solar wind (H^+ , He^{++}) and planetary ion species (H^+ , O^+ , O_2^+). In this approach, the Martian neutral environment above the exobase is modeled by spherically symmetric coronas of atomic hydrogen and oxygen, the height profiles of which depend upon the solar EUV flux. The in situ exospheric source of planetary ions is modeled through a self-consistent computation of the local production rate of each planetary species, H^+ and O^+ , for each ionization process (photoionization, electron impact, and charge-exchange) making use of charge exchange cross sections, ionization frequencies, given neutral densities, and computed plasma parameters (for details see Modolo *et al.* [2005]). The ionospheric reservoir is modeled by imposing the upward fluxes of the atomic and molecular oxygen ions at the altitude of the exobase (250 km). The spatial

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Table 1. Charge Exchange Reactions of He^{++} with Martian Neutrals

Channel ^a	Charge Exchange Reaction	σ (cm ⁻¹)
(1) ^b	$He^{++} + H \rightarrow He^+ + H^+$	3×10^{-16}
(2)	$He^{++} + H_2 \rightarrow He^+ + H_2^+$	2×10^{-16}
(3)	$He^{++} + He \rightarrow He^+ + He^+$	4×10^{-17}
(4) ^b	$He^{++} + O \rightarrow He^+ + O^+$	4×10^{-16}
(5)	$He^{++} + H_2 \rightarrow He + 2 H^+$	5×10^{-17}
(6)	$He^{++} + He \rightarrow He + He^{++}$	2.5×10^{-16}
(7) ^b	$He^{++} + O \rightarrow He + O^{++}$	2×10^{-16}

^aCross sections have been measured or compiled by: (1), *Barnett* [1990]; (2), *Kusakabe et al.* [1990]; (3), *Kimura* [1988]; (4), *Barnett* [1990]; (5), *Kusakabe et al.* [1990] and *Panov et al.* [2002]; (6), *Kimura* [1988]; and (7), *Barnett* [1990].

^bMost important processes.

resolution of these runs is equal to 300 km. In this paper we estimate the removal rate of solar wind He^{++} ions due to charge-exchange processes on the Martian atmosphere.

2. Hybrid and Test Particle Simulations

[4] The solar wind consisting of protons with number density $n(H^+) = 2.3 \text{ cm}^{-3}$ and He^{++} ions with number density $n(He^{++})/n(H^+) = 0.05$ flows with velocity $V_{sw} = 400 \text{ km s}^{-1}$ carrying the interplanetary magnetic field ($B_{IMF} = 3 \text{ nT}$). Although the hybrid simulations include self-consistently the dynamics of alpha-particles, the charge-exchange reactions involving He^{++} ions were not taken into account in the direct and consistent simulation because of their negligible effect on the global dynamics. In order to evaluate the removal of the solar wind He^{++} ions due to charge-exchange processes in the Martian atmosphere we need the positions and velocities of these particles with respect to the neutral species bound to the planet. In a stationary state of the Martian environment this information can be reconstructed by computing the motion of He^{++} test particles in the stationary and self-consistent electromagnetic field which is a stored output of the consistent three-dimensional hybrid simulation. While particle densities in the self-consistent hybrid simulation are computed as temporal snapshots from the instantaneous positions of the macroparticles, the same technique applied during a run of test particles would require an extremely large number of test macroparticles to reproduce the densities computed as snapshots during the consistent simulation. The computational effort is drastically reduced by adopting the methodology of test particle Monte-Carlo simulations [*Haviland*, 1965]. According to *Haviland* [1965] the density in a given volume of phase space is proportional to the residence time of the test particles in this volume. Indeed we do not compute exactly the residence time of the test particles in a given cell, but as the trajectory of each test particle is naturally sampled by the computational time step we just sum, at each time step, the contributions of each test particle to the simulation cells through which the particle is moving: the resulting number of counts in a given volume is thus proportional to the residence time of the test particle in that volume. The time step used for computing the motion of the test particles is small enough, and the number of test particles large enough, to sample correctly the computational domain. For a given number of injected test particles, 10^5 in the present case, their common initial statistical weight is

chosen in order to match the physical incoming flux of solar wind alphas. Each test particle is followed from its entry point, chosen at random on the entry face of the solar wind into the computational domain, up to its crossing of the exit face of the simulation box, or up to its final absorption in the dense atmosphere when it crosses the exobase: the weight of the test macroparticle is decreased by the charge exchange collisions as the test particle moves through the neutral background.

[5] The densities of He^{++} ions, computed as snapshots during the self-consistent hybrid simulation, and by integrating along the trajectories of test particles, are in good agreement despite slight differences due to the suppression of the self-consistent temporal fluctuations when using the frozen field with the test particles. The test particle method using the frozen stationary self-consistent field reproduces very well the positions of the bow shock and the magnetic pileup boundary (MPB) fitted from the MGS observations [*Vignes et al.*, 2000]. Both schemes give results enough similar to justify the used test-particle approach. The MPB, characterized by a sharp jump in the magnetic field strength and an increase in the magnetic field line draping [*Acuña et al.*, 1998; *Bertucci et al.*, 2003], is the boundary of the induced magnetosphere formed at Mars [*Dubinin et al.*, 2006].

[6] Alpha particles can be removed from the solar wind by charge exchange reactions with the main Martian neutrals above the exobase: atomic and molecular hydrogen, helium, and atomic oxygen. Table 1 gives the reactions together with their cross sections at 1 keV/amu and the references of the measurements: channels (1) to (4) produce He^+ through single electron capture, and channels (5) to (7) produce He atoms through double electron capture. We consider neither molecular nitrogen, nor carbon monoxide or dioxyde as they are important only below 200 km altitude. Let us notice that channel (6) influences neither the balance of solar wind alpha particles, nor the balance of He atoms in the atmosphere, and thus is not considered. In order to estimate the most important channels we have computed the local reaction rates at 300 km by making use of the density model of *Krasnopolsky* [2002, hereafter K2002], and at 2000 km using *Krasnopolsky and Gladstone* [1996, hereafter KG1996], corrected by the ratios of densities at 300 km between *Krasnopolsky* [2002] and *Krasnopolsky and Gladstone* [1996]. For atomic oxygen at 300 km and 2000 km altitude we have taken into account both the cold and hot coronas according to *Kim et al.* [1998].

[7] The most important processes, as noted in Table 1, are the charge-exchange reactions with the neutral atoms of oxygen and hydrogen which produce neutral and singly ionized helium. Concerning the local removal rate of solar wind alphas during solar minimum conditions, the case investigated in this paper, these three channels account for 94% of the total at 300 km and for 93% at 2000 km. During solar maximum, these percentages decrease to 85% and 70% respectively: missing contributions come mainly from the helium and molecular hydrogen coronas, the latter contributing only at high altitude. During solar minimum conditions, 96% of the local production rate of He atoms by double electron capture at low altitude is explained by the sole channel (7), i.e., the contribution from the atomic

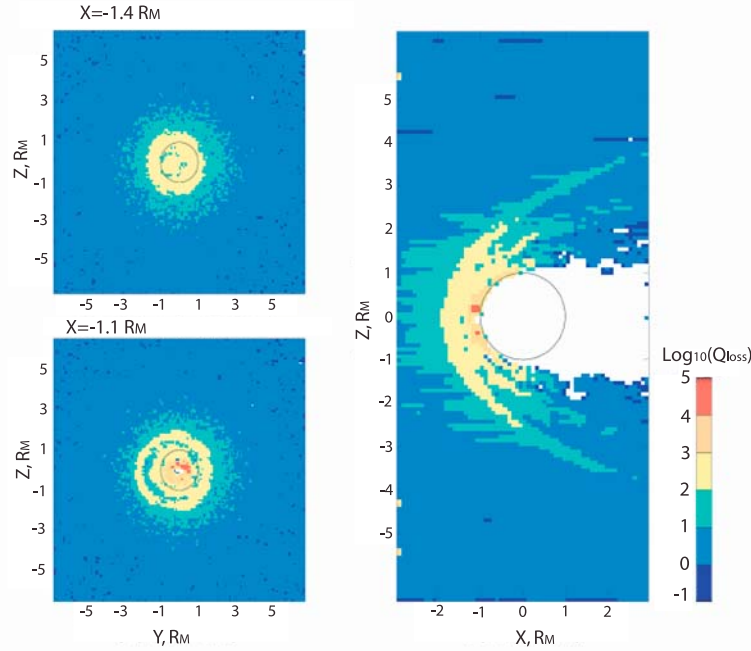


Figure 1. Maps of the removal-rate $Q_{\text{removal}}(m^{-3}s^{-1})$ of solar wind α -particles in different planes. Y-Z planes at $X = -1.1R_M$ and $-1.4R_M$ are located upstream of the planet, respectively just downstream of the bow shock and just above the exobase. Plane XZ contains both the bulk velocity of the solar wind and the IMF.

oxygen corona. At high altitude this fraction decreases to 45% as the contribution from the molecular hydrogen corona, through channel (5), becomes dominant. The same behavior is found during solar maximum conditions although with a smaller importance of the hydrogen corona. Nevertheless the direct production of He atoms being about 1000 times larger at 300 km than at 2000 km we disregard the contribution from the molecular hydrogen corona. In any case, neglecting this production leads to an underestimation of the production of He atoms.

[8] Figure 1 shows the maps of the removal rates of He^{++} ions. The right panel depicts the removal rate in the noon-midnight XZ-plane containing the vectors of the solar wind velocity (+X direction) and of the interplanetary magnetic field (+Z direction). An enhancement of the removal-rate is to be noticed at the location of the bow shock and of its fine structure composed of several “shocklets” in the sheath; it is due to the increase of the density of He^{++} ions. The strongest enhancement of the removal rate is observed near the magnetospheric boundary where the increased residence time of the alpha-particles combines with the increase of the atmospheric number density, leading to an enhanced rate of charge-exchanges. The left plates present maps of the removal-rates in two YZ cross sections (the motional electric field $-\mathbf{V}_{sw} \times \mathbf{B}_{IMF}$ is along the Y-axis) at $X = -1.4R_M$ and $X = -1.1R_M$. It is observed that most of removed solar alpha particles have an impact parameter smaller than ~ 3700 km. The total removal-rate of He^{++} ions is $6.8 \times 10^{23} s^{-1}$ which represents $\sim 30\%$ of the total flux of solar wind alpha-particles through a cross sectional area of radius $r = 3700$ km, i.e., the planetary radius augmented by

the altitude of the exobase. Removed solar wind alpha particles are transformed either into He^+ ions by single electron transfer on planetary neutrals, or into He atoms by double electron capture. The total removal rate is thus a majorant of the total deposition rate of helium atoms into the Martian atmosphere.

[9] Singly-ionized helium ions originating from the solar wind α -particles can be further transformed into neutral atoms by subsequent single electron transfer on Martian neutrals. However the efficiency of two-step processes to produce neutral helium is less than the efficiency of the one-step process by double-electronic capture $He^{++} + O \rightarrow He + O^{++}$. Part of the produced He-ENAs will impact the exobase and be captured in the lower atmosphere, while another part will escape to space. In general, Monte-Carlo simulations are required to predict the fate of energetic neutrals impacting the atmosphere. Here we present only a simple estimate of the fraction of helium ENAs impacting the exobase. On the entry face of the simulation domain, through which He^{++} ions are injected, we consider four circular and concentric zones having equal areas. The bounding radii of these zones are correspondingly R_{ex} , $\sqrt{2}R_{ex}$, $\sqrt{3}R_{ex}$, $2R_{ex}$, where $R_{ex} = R_M + h_{ex}$ (here $R_M = 3393$ km is the planetary radius, and $h_{ex} = 250$ km is the exobase height). 25000 He^{++} particles/per zone are injected with the same initial statistical weight. The numbers of He-atoms impacting the exobase, and that were produced by ‘mother-ions’ launched in the different zones, are calculated. The total contributions to the flux of neutral helium from zones 1–4 are respectively 1.5×10^{23} , 4.4×10^{19} , 1.4×10^{18} , 2.6×10^{15} atoms s^{-1} , i.e., α -particles

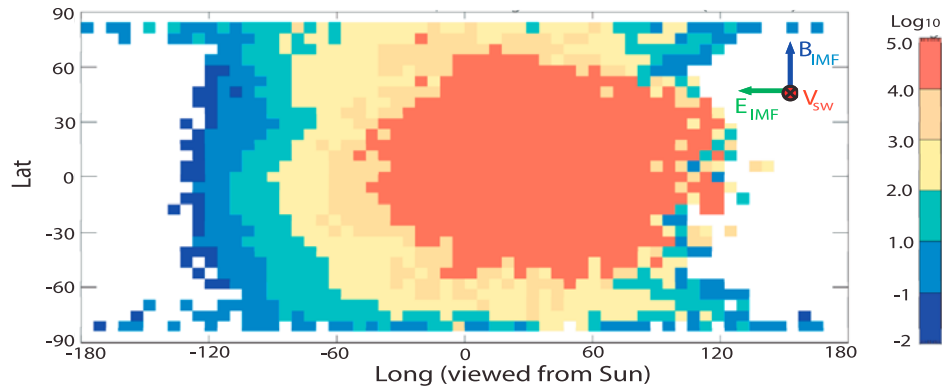


Figure 2. Flux of He -atoms ($\text{cm}^{-2}\text{s}^{-1}$) impacting the exobase of Mars in the latitude-longitude coordinates: latitude and longitude are just names given to the polar angles, they do not have their usual geographical meaning. The point with $\text{Lat} = 0$, $\text{Long} = 0$ corresponds to the subsolar point. The IMF is directed from the south to north. The interplanetary electric field is antiparallel to the longitude axis.

originating in zone 1 contribute for the major part. Figure 2 shows the latitude-longitude distribution of He -atoms, impacting the exobase, that were produced by ‘mother-ions’ injected into the computational domain through zone 1 ($R = \text{Rex}$). Angles called “latitude” and “longitude” do not have here their usual geographical meaning as long as neither the crustal magnetic field nor the planetary rotation are taken into account: there are indeed just polar angles used to locate a point on a sphere. The interplanetary magnetic and electric fields are parallel to the latitude axis and antiparallel to the longitude axis, respectively. A longitude-asymmetry of the impacts in the $-E_{\text{IMF}}$ direction is clearly observed. A similar asymmetry may also be expected in the distribution of neutral helium near Mars, and in the distribution of the sputtered atoms which contribute to the loss processes.

3. Conclusion

[10] It has been shown that the capture of solar wind α -particles in the exosphere/atmosphere can strongly influence the He budget on Mars. The removal rate of He^{++} solar wind ions due to charge-exchange processes provides us with an upper limit of the deposition rate of helium on Mars equal to $6.8 \times 10^{23} \text{ s}^{-1}$. This value has the right order of magnitude to compensate for the loss rate of the planetary helium ($8 \times 10^{23} \text{ s}^{-1}$) estimated by Krasnopolsky and Gladstone [2005]. He^+ -ions created by charge exchange can also contribute significantly to the observed fluxes of singly ionized He at Mars, beside the ionization of neutral helium, and therefore the problem of loss and source processes of helium should be considered self-consistently. Further studies involving Monte-Carlo simulations are needed to refine the helium budget at Mars.

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